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ation and thermo-optical properties of the MLS composite primary reflector

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ABSTRACT

The Microwave Limb Sounder (MLS) is a limb-sounding radiometer sensing emissions in the millimeter and sub-millimeter range. MLS will contribute to an understanding of atmospheric chemistry by assessing stratospheric and tropospheric ozone depletion, climate forcings and volcanic effects. The heart of the antenna is the primary reflector, constructed from graphite/cyanate composites in a facesheet/core construction. The reflector has an aperture of one square meter, a mass of 8.7 kilos and final figure accuracy of 4.37 microns rms. The surface is also modified to ensure RF reflectivity, prevent solar concentration and provide thermal balance to the spacecraft. The surface is prepared by precision bead-blasting, then coated with vapor deposited aluminum (VDA) and finally a layer of silicon suboxide (SiOx) to control the infrared emissivity. The resulting surface has a solar absorptance of 0.43 and an absorptance/emittance ratio of 1.3. BRDF analysis shows that 93% of the incident thermal energy is reflected outside a 10 degree angle of cone. For its mass and aperture, we believe this reflector to have the highest figure accuracy yet achieved in a composite antenna construction.

Keywords: **EOS, MLS, composites, reflectors, microwaves, coatings, silicon suboxide, ozone**

1. INTRODUCTION

In 2002, NASA will launch its Earth Observing System's (EOS) CHEM satellite into polar orbit on a Delta rocket. Once in orbit the CHEM satellite is designed to measure key chemical compounds in the lower atmosphere and answer three major questions; is the Earth's ozone layer recovering, is the air quality changing and how is the overall climate of the Earth changing? The CHEM spacecraft is being designed by TRW to provide the pointing accuracy and stability needed by its four instruments to take precise measurements. The spacecraft is built with lightweight composites and powered with high reliability nickel-hydrogen batteries. The Microwave Limb Sounder (MLS) is one of the four instruments of the CHEM satellite. The MLS measures thermal microwave radiation emitted by ozone, chlorine compounds and many other trace gasses. Additionally, measurements of upper tropospheric water vapor will clarify the role this greenhouse gas may play in global warming.

1.1 Microwave Limb Sounder (MLS)

The MLS instrument comprises three modules; Gigahertz (GHz), Terahertz (THz) and Spectrometer. The GHz Module consists of the Antenna and Radiometer. The Antenna is a 3-reflector clear-aperture offset Cassegrain system which collects and focuses millimeter and sub-millimeter emissions into the Radiometer. There, optics frequency-multiplex the signal and direct it to each of five Receivers centered at 118 (2), 190, 240 and 640 GHz frequencies. These receivers, along with 2nd IF (Intermediate Frequency) stages, amplify and down-convert the signal, then deliver it to spectrometers in the Spectrometer Module for final processing before collection by the Command and Data Handling (C&DH) Assembly for transfer to the spacecraft. The THz Module performs the same basic functions for the 2.5 THz frequency measurement as the GHz module, also delivering a 2nd IF output to the Spectrometer Module.

2. MLS PRIMARY REFLECTOR

The heart of the GHz Module is its large Primary reflector. The front surface of the reflector is an off-axis parabolic surface, with a focal length of one meter, an elliptical projected aperture, and serves to collect the RF beam and aim it onto the prime focus shared by the hyperbolic Secondary reflector. Its projected aperture is: 1.6 meters, major axis, by 0.8 meters, minor axis (62.99 inches by 31.496 inches). A photograph of the completed MLS primary reflector is shown in Figure 1., along with a section of the triangular isogrid core.

Figure 1. Lightweight, Thermally Stable
Composite MLS Primary Reflector

2.1 Primary reflector: performance requirements

The Primary reflector is of composite facesheet/core sandwich type construction. The facesheets are composite based on a high modulus graphite fiber with a cyanate ester resin matrix. B-basis material properties (90% probability, 95% confidence) were found acceptable for all composite constructions. Edge closure of the reflector sandwich is not required for instrument performance, and the core must allow for venting of the contained gases at launch. During the nominal orbit, the Allowable Flight Temperature (AFT) range for the Primary reflector is -50(C to +110(C.

Surface accuracy of the reflector consists of error of form, surface figure, and surface finish. The error of form is defined as deviation of the best-fit reference surface from a nominal surface. This comprises five rigid-body motions consisting of three translations, two tilts and the difference in focal length. The nominal surface for the Primary reflector is a section of a paraboloid, referred to as the parent paraboloid. Surface figure accuracy is defined as the deviation of the measured surface profile from a best fit reference surface, and is limited to the long wavelength deviations having a peak-to-peak spacing along the surface of the reflector of 0.025 cm (0.010"), or larger. The surface figure (figure accuracy) has a minimum requirement of 8.5 microns (0.00033") root-mean-squared (rms) at a 90% confidence level.

Surface finishing of the Primary reflector is a separate operation. This requires grit-blasting and coating of the surface in order to reflect sunlight diffusely for temperature control, and to prevent thermal loading of the other reflectors in the optical train. The Primary reflector front surface is required to meet the following needs: (a) RF reflectance in the sub-millimeter wavelengths out to 640 GHz (470 microns wavelength), (b) a specular reflection of sunlight of < 10% (at a 10o angle of cone), (c) a solar absorptance <0.40, and, (d) a ratio of solar absorptance to infrared emittance of 1.0 < (/(< 2.0 . With these requirements met, the Primary reflector will permit the signal to be acquired without undue thermal loading of itself or other components of the optical train.

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The primary reflector was designed and fabricated by Composite Optics, Inc. (COI), San Diego, CA., and consists of two identical composite faceskins adhesively bonded to a lightweight composite core rib structure.

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The two 24 ply faceskins were fabricated from graphite/ cyanate unidirectional prepreg tape stacked in a pseudo-isotropic pattern (0(, 45(, 90(, 135()S3 . Total laminate thickness for both front and back faceskins is 0.060 inches. The faceskins were fabricated and autoclave cured on a bulk graphite mold of convex parabolic shape, and machined to a surface accuracy of 2.5 microns rms. The skins used a unique gore pattern to accommodate the double curvature of the mold.

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The primary reflector was assembled on the same bulk graphite tool used to fabricate the front and back face skins. The first step was to vacuum bag the front skin to the mold so that it tightly conformed to the mold contour. The ribs were carefully contoured to shape and were then bonded to the front face skin using a room temperature curable epoxy adhesive. Bondline thickness was held to less than 5 mils to provide intimate contact between the ribs and facesheets. Figure 2. shows the reflector with the front face vacuum bagged to the graphite mold and the internal ribs bonded to the front face. The back skin was then bonded to the core ribs to form the completed sandwich structure. Three triangular Invar interface fittings were machined to fit through holes in the back skin and were bonded to the core ribs. Tooling balls were installed on the front surface at the ends of the major and minor axes to establish reference points for figure metrology and optical alignment purposes.

Figure 2. MLS Composite Primary Reflector
During Assembly on Graphite Mold

3. SURFACE FINISHING OPERATIONS

A special surface was designed for the Primary reflector to meet the RF reflectance, solar specularity and thermo-optical property requirements. Low specularity, achieved by grit-blasting the surface, was needed to prevent sunlight from thermally loading the other elements in the optical train. A carefully controlled grit-blasting procedure was accomplished by mounting the Primary reflector on the bed of a CNC (Computer Numerically Controlled) gantry mill, and replacing the usual tool bit with a specially designed grit-blasting nozzle. An aluminum oxide grit was used with a mean particle diameter of 17 microns. This was sprayed on the surface with a nozzle pressure of 40 psi, and a nozzle feed rate of 100 inches/minute. A CNC program was written to follow the contour of the reflector and maintain a constant height of 2 inches above the surface. The nozzle traveled along the Y axis (major axis) of the reflector and stepped over by 0.100" at the completion of each travel. The resulting surface was uniformly abraded and dull in appearance. It was cleaned with an aqueous soap solution, International Laboratory's Micro-9 cleaner, followed by distilled water and alcohol. Very little cut-through of the surface was observed, and almost no carbon black resulted from abraded carbon fibers.

Surface cleaning and subsequent vacuum deposition processes were conducted at Surface Optics Corporation (SOC) in Rancho Bernardo, CA. Vapor Deposited Aluminum (VDA) was deposited to a thickness of 1.2 microns at a pressure of 10-6 Torr. This coating meets the five skin-depth requirement for adequate RF reflectance, and also reduces the absorbance of sunlight which would thermally load the reflector. Ultra-pure wire-fed aluminum was used for this operation. Due to the low emittance of aluminum a second coating was required to meet the thermo-optical requirements. Silicon suboxide (SiOx) was selected due to its good adhesion to aluminum and its relatively high infrared emittance. This coating was achieved by reactive evaporation in which silicon monoxide was deposited on the reflector in the presence of a very low pressure of oxygen1.. The resulting oxide coating had a thickness of 0.8 microns. The grit-blasting conditions, materials selection, and thicknesses were previously determined from a large test matrix.

Measurements of the final properties were done on witness coupons simultaneously subjected to the entire sequence of grit-blasting and coating operations. The results showed an average solar absorptance (() of 0.43, an infrared emittance (() of 0.330, and an absorptance-emittance ratio ((/() of 1.30. Light scattering was determined by BRDF (Bi-directional Reflective Distribution Function) and found to provide diffuse reflection of 93% of the incident solar energy outside of a 10 degree angle of cone.

4. FIGURE ACCURACY MEASUREMENTS

The figure accuracy of the resulting Primary reflector was determined with the use of a Coordinate Measuring Machine (CMM) (Brown and Sharp, Validator 7236, operated by Composite Optics, Inc.). The CMM machine had been recently rebuilt with high accuracy rotary encoders and the newest version of PC-DMIS software. Statistical experiments indicate a machine accuracy of approximately 1.5 microns, rms.

The primary reflector was mounted on the CMM table and its true position determined from permanently mounted tooling balls. The CNC controlled CMM was programmed to take x, y and z measurements as a set of 1,437 points over the surface of the reflector. The measurements was then corrected for displacements due to rigid body piston and two tilts, and then transformed to an unconstrained best-fit paraboloid. The residuals from statistical comparison with the mathematical parent paraboloid resulted in the root-mean-squared figure accuracy. CMM measurements were performed after initial fabrication, thermal cycling from –80(C to +90(C (10 cycles at 2.3(C/min), thermal/vacuum exposure and acoustical testing at JPL, surface grit-blasting, and following final coating pre-delivery. Table 1. gives results of these measurements, and Figure 3. shows a typical primary reflector figure error contour map. These measurements have been run many times on the reflector, and also on the graphite mold used for facesheet fabrication and reflector assembly. It may be noticed that the figure error measured on the completed reflector directly maps to the same pattern of errors measured on the mold surface. The graphite mold was determined by CMM to have a surface accuracy of about 2.5 microns. This is at the very limit of machine resolution, and at this level the molded composite surface appears to replicate the mold within a factor of two.

Table 1. Primary Reflector Figure Accuracy (CMM)

As Fabricated 4.50 u rms After Thermal Cycling 4.39 u rms After Thermal Vacuum & Acoustical Testing 4.45 u rms Following Grit-Blasting 4.52 u rms Final: Following Coating 4.37 u rms

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Figure 3. Typical Primary Reflector Figure Contour Map

4.1 Performance analysis

The results shown in Table 1. indicate the robust design and excellent thermal stability of the reflector. Figure 3. shows a typical figure contour map as determined by measured CMM measurements. The contour map shows an identical pattern of errors as the map generated for the mold surface itself, and each CMM measurement of the reflector surface varies only slightly in the amplitude of the error; the features being virtually the same. Table 2. compares the required and actual performance for the MLS composite primary reflector. The reflector exceeded all of the requirements except for a seven percent excess in the solar absorptance. This was marginally in excess of the original design target, but is easily accommodated in by the thermal balance of the spacecraft. Despite the large experimental test matrix and meticulous process control, this property is difficult to control and does not easily scale to large sizes.

Table 2. MLS Composite Primary Reflector Performance

Parameter	Requirement	Actual

Dimensions	1.6 x 0.8 meter ellipse	Same
Mass	10 kg (22.05 lb)	8.6 kg (19.1 lb)
Areal Density	7.8 kg/m2	6.7 kg/m2
Stiffness	80 Hz	228 hz (kinematic, calculated)
Surface Accuracy (as-fabricated)	8.5 microns rms	4.37 microns rms (measured)
Surface Stability (on-orbit environment)	18 microns rms	6.1 microns rms (calculated-no correction)
Absorptance	0.40	0.43
Absorptance/emittance	1 < (/(< 2	1.3

5. CONCLUSIONS

This project has demonstrated the feasibility of fabricating light-weight, high figure accuracy reflectors using innovative composites technology. The result of this work has also delivered a critical piece of flight hardware to the EOS Project within the constraints of mass, figure accuracy, environmental stability and thermo-optical performance. The excellent replication of the mold surface combined with current concepts for polishing and error correction suggests that much higher figure accuracies should be possible.

The future of composite reflectors

One figure-of-merit for optical elements is to divide the aperture (square meters) by the mass (kilograms) times the surface accuracy (microns, rms). Using this as a metric, the MLS primary reflector has twice the figure of merit in comparison to the new Gemini 8.1 meter glass reflector recently installed at the Mauna Kea observatory. Although the two reflectors are dissimilar in manufacture and performance, advances in error correction techniques may eventually permit large optical elements based on composite materials to operate in the visible wavelength ranges.

ACKNOWLEDGEMENTS

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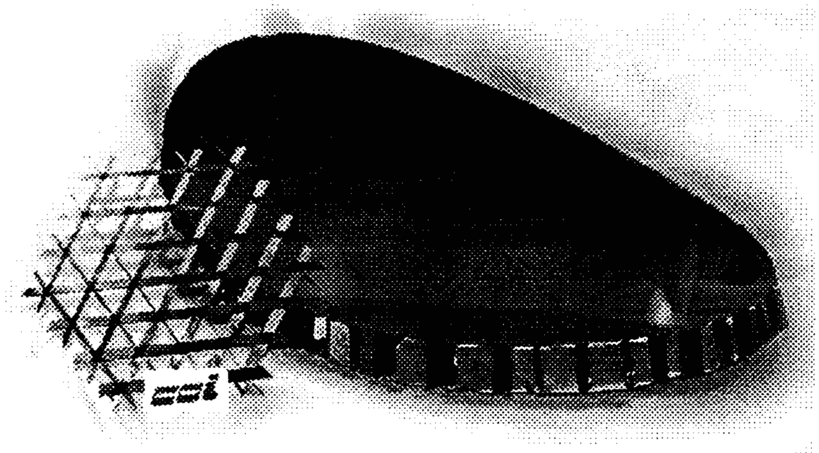

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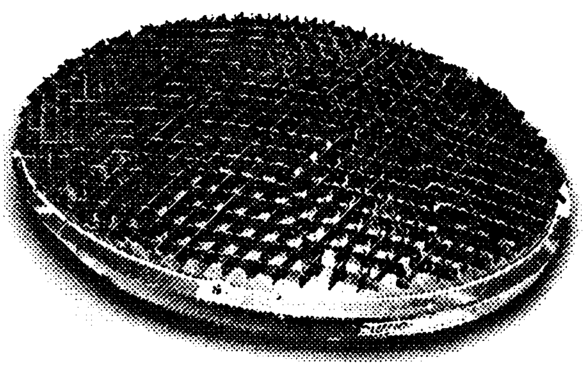

Figure 2. MLS Composite Primary Reflector During Assembly on Graphite Mold

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Table 1. Primary Reflector Figure Accuracy (CMM)

As Fabricated	4.50 u rms
After Thermal Cycling	4.39 u rms
After Thermal Vacuum & Acoustical Testing	4.45 u rms
Following Grit-Blasting	4.52 u rms
Final: Following Coating	4.37 u rms

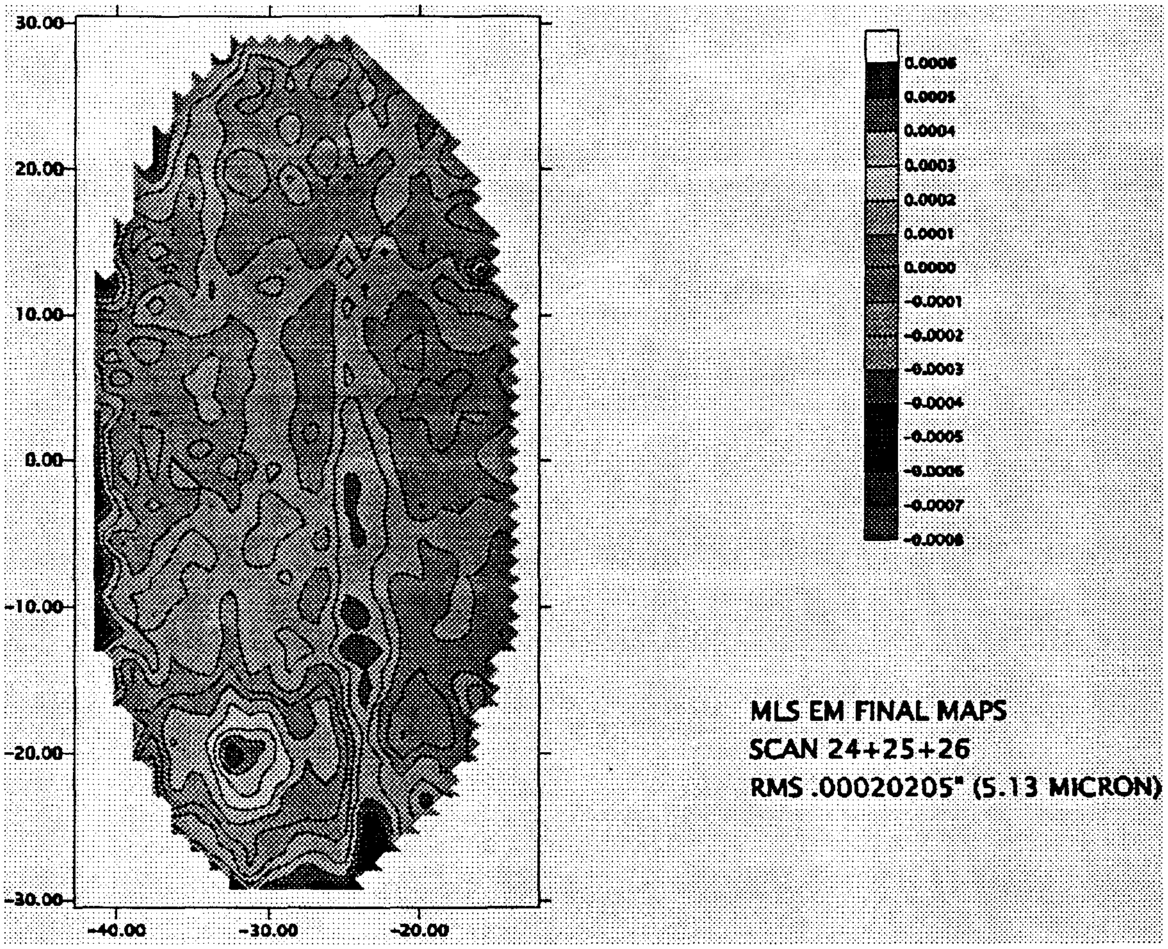

Figure 3. Typical Primary Reflector Figure Contour Map

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Table 2. MLS Composite Primary Reflector Performance

Parameter	Requirement	Actual
Dimensions	1.6 x 0.8 meter ellipse	Same
Mass	10 kg (22.05 lb)	8.6 kg (19.1 lb)
Areal Density	7.8 kg/m^2	6.7 kg/m^2
Stiffness	80 Hz	228 hz (kinematic, calculated)
Surface Accuracy (as-fabricated)	8.5 microns rms	4.37 microns rms (measured)
Surface Stability (on-orbit environment)	18 microns rms	6.1 microns rms (calculated-no correction)
Absorptance	0.40	0.43
Absorptance/emittance	$1 < \alpha/\varepsilon < 2$	1.3

5. CONCLUSIONS

This project has demonstrated the feasibility of fabricating light-weight, high figure accuracy reflectors using innovative composites technology. The result of this work has also delivered a critical piece of flight hardware to the EOS Project within the constraints of mass, figure accuracy, environmental stability and thermo-optical performance. The excellent replication of the mold surface combined with current concepts for polishing and error correction suggests that much higher figure accuracies should be possible.

5.1 The future of composite reflectors

One figure-of-merit for optical elements is to divide the aperture (square meters) by the mass (kilograms) times the surface accuracy (microns, rms). Using this as a metric, the MLS primary reflector has twice the figure of merit in comparison to the new Gemini 8.1 meter glass reflector recently installed at the Mauna Kea observatory. Although the two reflectors are dissimilar in manufacture and performance, advances in error correction techniques may eventually permit large optical elements based on composite materials to operate in the visible wavelength ranges.

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